PROJECT APOLLO

AIRCRAFT COMMUNICATION RANGE AND DEPLOYMENT FOR RECORDING SIGNALS FROM THE SPACEVEHICLE DURING INJECTION

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ABSTRACT

It is highly desirable that conditions aboard the Apollo spacevehicle be monitored and recorded at the time it is injected into a lunar transfer trajectory. However, injection may take place in an area that is remote from the ground support network, and for this reason consideration is given to the use of aircraft for recording voice and telemetry transmissions from the spacevehicle. The recording period considered in nine and one-half minutes, made up of one minute before the start of burn, five and one-half minutes during burn, and three minutes after burn. Both VHF and S-band transmissionswould be recorded.

Based on what appear to be reasonable assumptions, it is found that two aircraft, properly stationed and provided with suitable radio equipment, can cover the injection period. One would cover the first, or low altitude, portion of the track, and the other, the last, or higher altitude portion. Large antennas and low-noise receivers are required in the aircraft. Because of launch delays, and because of the possibility of injecting on any one of three orbits, it is not possible to determine ahead of time just where the aircraft should be stationed. Thus, additional aircraft are required because of the rapid westward movement of the injection opportunities. Five jet aircraft (not counting spares) would be needed to cover injection on any one of three orbits in the Pacific if the launch azimuth spread in any one day is no more than 26 degrees.

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1. INTRODUCTION

It is probable that the Apollo spacevehicle will not be within communication range of a ship or shore station at the time it is injected into translunar flight. Nevertheless, it is important that conditions aboard the spacevehicle be monitored during and just after this powered phase of the mission. This memorandum considers some of the aspects of a proposal that has been made by NASA to utilize C-135 type jet aircraft to record communications in the remote areas where injection may occur.

The communication links studied here are limited to those required for recording purposes, that is, one-way radio channels from the spacevehicle to the aircraft. It is desired to record voice and telemetry transmissions during the approximately five and one-half minute burn period and for about three minutes thereafter. In addition, a recording time of one minute preceding the beginning of powered flight has been proposed. Thus, the total period of radio contact would be about nine and one-half minutes. The stored information would be analyzed on the ground at a later time.

The information to be recorded will be radiated at VHF and S-band frequencies and will originate in three different sections of the spacevehicle: the Command/Service Module (CSM), the Instrumentation Unit (IU), and the S-IVB booster. There is a total of 10 radio channels to be recorded, as follows:

<u>From the Command/Service Module</u>

- 1 VHF Double-Sideband (AM) Voice Circuit
- 1 VHF PCM/FM Telemetry Circuit at 51.2 kbps
- 1 VHF PAM/FM/FM Telemetry Circuit
- 1 Unified S-band Circuit for Voice, Telemetry (at 51.2 kbps), and Ranging

<u>From the Instrumentation Unit</u>

- 1 VHF PCM/FM Telemetry Circuit at 72 kbps
- 1 VHF PAM/FM/FM <u>or</u> SSB/FM Telemetry Circuit
- 1 S-band PCM/FM Telemetry Circuit at 72 kbps

<u>From the S-IVB</u>

- 1 VHF PCM/FM Telemetry Circuit at 72 kbps
- 2 VHF PAM/FM/FM <u>or</u> SSB/FM Telemetry Circuits

It is understood that all of these circuits may be used simultaneously; thus, the recording system must be capable of handling at least 10 channels. At the present time, it is not known whether the PAM/FM/FM or the SSB/FM system will be instrumented for the Apollo LOR mission. The latter system will perform as well as, or better than, the former system if the carrier-to-noise ratio in a given RF band is above the FM threshold. On this basis, the PAM/FM/FM system has been selected for the transmission studies in this memorandum.

It is further understood that the S-band systems will operate in the 2200-2300 mc range, and that the VHF systems will be allocated frequencies in the 216-260 mc range for telemetry, and in the 290-300 mc range for double-sideband AM voice.

All systems except the unified S-band (in the CSM) will have a single mode of operation which will be established before the mission. The CSM S-band system may operate in any one of several modes. It is assumed that there will be a pre-arranged schedule for the use of these modes, but with the possibility of an astronaut override if conditions should warrant it. There are three modes that are representative of the types of signals that might be generated during the translunar injection and they have been singled out for studies of their transmission performances. They are:

Mode A - voice and 51.2 kbps telemetry
Mode B-1 - voice, 51.2 kbps telemetry, and ranging
Mode F - emergency voice

In addition to the analysis of transmission performance of the various radio channels, estimates are made in this memorandum of the number and location of aircraft (at 7 nautical miles altitude) required to cover the nine and one-half minute injection period. Because of launch delays and orbital flight check-outs, the time and location of injection cannot be predicted sufficiently far in advance to station aircraft in the optimum positions. For this reason, the operational problem has been analyzed and an estimate made of the minimum number of aircraft required to cover the injection opportunities in one ocean area on a single day.

2. SUMMARY

If a monitoring aircraft is to receive satisfactory VHF and S-band signals from the spacevehicle, the first requirement is for a line-of-sight transmission path with some clearance over the earth. Although an aircraft at an altitude of 7 nm can be stationed to "see" the spacevehicle for the entire injection period of nine and one-half minutes, this requirement is not controlling. A second, and more basic, requirement is that the received carrier-to-noise ratios provide circuits of acceptable quality for voice and telemetry. The principal items that make it difficult to meet this latter requirement are (1) the low transmitter powers (in the spacevehicle), (2) the considerable path loss, (3) limited antenna gain that can be provided in an aircraft, and (4) severe multi-path fading at low elevation angles because of the near-unity reflection coefficient of sea water.

The maximum size antennas suitable for C-135 jet aircraft have been assumed to be a 6-foot dish for S-band frequencies and an 8.5 x 8.5 foot array for VHF. The gains have been estimated to be about 30 db and 15 db, respectively. The use of smaller antennas would seriously affect the conclusions in the next paragraph - particularly those relating to VHF.

In order to reduce multi-path fading to an acceptable degree (taken here to be 6 db), it will be necessary to specify a minimum elevation angle between the horizon and the spacevehicle. If the elevation angle is kept above this minimum, it will be possible to use the aircraft antenna pattern to discriminate against ground-reflected radio waves. This procedure reduces the allowable distance between the aircraft and the spacevehicle. If only S-band frequencies were used, the reduction would be less because of the narrower antenna beamwidth. However, the VHF system, with its wider antenna beam, is controlling, and the minimum elevation angle becomes about 10 degrees. With this limitation, two aircraft, properly stationed, will be needed to cover a specific, 9 1/2-minute long injection path. The transmission margins for the various radio circuits at maximum range (occurring three minutes after the end of burn) are given in the following table:

Radio Circuit VHF	Approximate Transmission Margin, in db
Double Sideband Voice (CSM)	7.5
PCM/FM 51.2 kbps Telemetry (CSM)	-1.5
PCM/FM 72 kbps Telemetry (IU & S-IVB)	0
PAM/FM/FM IRIG Telemetry (IU & S-IVB)	-1.5
S-band (IU)	
PCM/FM 72 kbps Telemetry	6.5
Unified S-band (CSM)	
Mode A - FM/PM Voice	6.0
PCM/PM/PM 51.2 kbps TLM	0.5
Mode B-1* - FM/PM Voice	4.5
PCM/PM/PM 51.2 kbps TLM	-1.0
Mode F - Emergency Voice (Without Power Amp.)	1.0

It should be emphasized that the margins cited above apply near the end of the 9-1/2 minute recording period. From one minute prior to burn until about one minute after the burn, the margins would be at least 6 db greater than listed in the table.

Two important assumptions have been made in deriving these results: (1) that radio wave attenuation through the exhaust plume of the S-IVB will be negligible, and (2) that the variable RF losses in the system (fading, antenna pattern variations, equipment degradation, etc.) add in a random manner. Results of the Saturn SA-5 test flight tend to support

*"Up" Mode 1-A (ranging only) should not be used with this "Down" Mode since the margins will deteriorate by about 5.5 db.

the first assumption, but further verification is desirable. The transmission situation at maximum range is marginal at best, and even a few db loss in the rocket flame could be serious.

With regard to the variable RF losses, if all of them should maximize at the same time (so that they add arithmetically), the attainable radio ranges at VHF would be cut in half and the transmission margins reduced by 6 db. The effect at S-band would be somewhat less: about 3.5 db instead of 6 db. On the other hand, if the RF loss variations should be less than those that have been assumed, the transmission performance may be expected to be better than that shown in the table.

Subject to the preceding comments, the conclusion drawn here is that a specific nine and one-half minute injection period could be covered satisfactorily with two aircraft, but not with one. The negative margin of 1.5 db for two of the VHF telemetry channels is not believed to be significant; there would be no sudden transmission impairment, but some fading may be expected during the final portion of the recording period.

Two aircraft can cover the injection period if the location of the injection path is known sufficiently far in advance - that is, far enough for the aircraft to travel to the appropriate monitoring locations. However, this is not expected to be the situation, and it becomes necessary to provide enough aircraft to cover all injection opportunities. Simple economics demands that the number of aircraft be kept to a practical minimum.

The basic problem is that the aircraft cannot keep up with the westward drift of the injection opportunities. To do this, the aircraft speed would have to equal that of the earth's rotation at the equator - about 900 knots. The number of aircraft can be minimized by stationing them between desirable monitoring locations, and then dispatching them to one location or the other as the situation requires.

It has been estimated that, for a launch azimuth spread of 26 degrees and for injection over the Pacific Ocean on any one of three orbits, five aircraft will be required. This does not include back-up aircraft. If it can be determined in advance that injection will occur on one of two orbits, either the first and second or the second and third, only four aircraft would be required. Actually, the latter situation (second or third orbit injection) could be covered by as few as three aircraft provided their endurance (time in the air) is adequate. This is based on the distances that must be traveled between the injection areas and the potential aircraft bases in the Pacific Ocean.

3. RECORDING SYSTEM

3.1 Recorder-Reproducer

Early in this study, a basic decision had to be made regarding the form in which the signal should be recorded. It was accepted that recording on magnetic tape is the most logical choice, but it remained to be determined if pre-detection or post-detection recording techniques should be employed. As discussed in Appendix A, pre-detection recording appears to be the more advantageous and is recommended for this airborne application. The principal reason is that it permits a reduction in the amount of equipment carried in the aircraft. The appendix also presents the results of a brief survey of existing pre-detection tape recorder-reproducers. It is found that there are several types that have sufficient capacity to record 14 channels for 12 minutes or more. This is more than adequate for the 10 channel, 9-1/2 minute requirement, thus providing tracks for recording AGC voltages, timing signals, etc.

With pre-detection recording, it is unnecessary to provide radio terminal or data processing equipment in the aircraft. However, in the absence of such equipment, there may be some difficulty in determining whether or not the signals from the spacecraft are actually being received. Thus, some minimum amount of terminal equipment should be provided (e.g., voice receiving equipment), and, in addition, each channel should be provided with an alarm circuit that recognizes the presence or absence of the radio signal assigned to it.

3.2 Over-all System

The material in Appendix A has established the basis for a description of the overall recording system. This is shown in Figure 1. The left hand portion of this figure lists the communication systems in the space vehicle. The right hand portion shows in block diagram form the implementation proposed for the aircraft. The general procedure for handling each signal is to translate - in one case, demodulate - the received RF signal spectrum so that it will fit into the frequency response of one track of the recorder-reproducer.

For the VHF signals, the first step of the translation process would be accomplished by a standard VHF telemetry receiver - front end and IF strip. In this step the signal would be converted to the normal IF frequency (5 or 10 megacycles). This output would then be converted, or translated, to another IF frequency that is near the center of the frequency response of the recorder-reproducer. The latter IF frequency would normally be in the 600 to 800 kc range with the final selection for each channel depending on the signal spectrum characteristics and the recorder-reproducer characteristics. For instance, a narrow band amplitude modulation signal should be recorded in the part of the recorder-reproducer's frequency response where the signal-to-noise ratio and linearity are the best. This might be in the upper or the lower end of the frequency response band depending on the recorder-reproducer's design. Although a common center frequency for all channels might make the carrier design easier, the use of different center frequencies might help prevent interference between channels. It will be noted that IF bandwidths are specified for each channel. Present practice in VHF-PCM telemetry is to make use of standard IF bandwidths of 500, 300 and 100 kc. Since IF bandwidth is not too critical for pre-detection recording, the standard bandwidth used should be one that covers the spectrum of the signal plus doppler shift and oscillator drift. These bandwidths are given in Section 4.5. In most instances, the demodulation bandwidth used at the ground station could be made less than this value by utilizing carrier tracking techniques.

Recording of the S-band channel from the Instrumentation Unit would be comparable to the procedure for the VHF channels; that is, the signal would be converted to an IF frequency within the response range of the recorder, and then recorded without being detected.

The situation with the Unified S-band system from the CSM is somewhat more complicated. Since one cannot be sure when Mode F (Emergency Voice) might be used, and since its RF bandwidth is within the capability of the recorder-reproducer, a separate channel is shown at the top of the block diagram. This signal would be translated in the same manner as the VHF signals, that is, no demodulation would take place ahead of the recording process. However, as discussed in Appendix A, Modes A and B-1 have IF bandwidths that make it necessary to provide one stage of demodulation before the signal can be recorded. (Alternately, some non-standard method of demodulation might be used.) Since only one of these modes can be used at a given time, a single recorder channel is allocated for them. Succeeding stages of demodulation would be accomplished at the ground station during the reproducing process.

Other major units in the monitoring system are the multi-couplers. Since an aircraft has limited space for gain antennas, it is desirable that only one VHF antenna and one S-band antenna be used. The multi-couplers provide this capability. Depending on the filtering characteristics of the front ends of the receivers and the frequency assignments for the various signals, some additional filtering might be necessary to isolate the receivers from each other.

Three other items shown on the diagram are the VHF antenna, the S-band antenna, and the control system for pointing the antennas toward the spacecraft. The antennas will be discussed further in Section 4.4.

4. TRANSMISSION CONSIDERATIONS

4.1 Path of Spacevehicle

While in earth orbit, the Apollo spacevehicle is expected to be at an altitude of about 100 nm and traveling at a rate of 25,500 feet per second (about 4.2 nm per second). This will be the approximate situation at the time the SIV-B is ignited to start the spacevehicle on its translunar flight. At the end of the five and one-half minute burn period, the altitude will have increased to about 159 nm and the velocity to about 6 nm per second. Three minutes later the spacevehicle altitude is expected to be about 345 nm. The path of the spacevehicle, including the path during a one-minute period before the start of burn, is shown by the dashed line in Figure 2. Time is counted in minutes from the end of burn as noted on the figure. All distances are in nautical miles.

The altitudes and distances in Figure 2 have been obtained from Bellcomm, Inc. and apply to a 324-second burn period. The total distances covered by the spacevehicle between -6.5 minutes and +3 minutes are given in Table 1.

Table 1

Time Interval		Approximate Distances in nm: In Space	Approximate Distances in nm: On Surface
-6.5 to -5.5		252	245
-5.5 to 0		1630	1550
0 to +3		1035	945
	TOTAL	2917	2740

Communication with the spacevehicle must be maintained while it is covering these distances.

4.2 Line-of-Sight Distances

True Earth. Assume that the aircraft will fly at an altitude of 7 nm. Using a true earth radius of 3445 nm, the surface distance to the horizon from a point directly below the aircraft is 220 nm. The distance (on the earth's surface) from the spacevehicle at an altitude of 100 nm to the horizon is 820 nm. Thus, when a straight line between the aircraft and spacevehicle is tangent to the earth, the maximum surface distance between them is 1040 nm. When the spacevehicle is at an altitude of 345 nm (+3 minutes), the corresponding maximum straight line distance is 220 plus 1480, or 1700 nm.

Refraction. Atmospheric refraction causes a radio ray to follow a curved path, and this results in a radio horizon distance that is greater than the straight line distance to the horizon. Figure 3 illustrates this effect. The additional distance depends on the amount of atmosphere traversed by the radio ray, the angle of arrival of the ray, and, of course, on the refractivity of the atmosphere at the time and place in question. The greatest bending takes place at low altitudes (sea level) and at low angles to the horizon. The amount of bending decreases as the radio ray clears the earth by greater and greater distances.

A radio wave leaving the earth's surface at a zero degree elevation angle will attain one-third of its total atmospheric bending by the time it reaches a height of about 2,000 feet, and it will have bent two-thirds of the total by about 10,000 feet.[1] By the time it reaches 7 nm, the radio wave will have attained about 96 percent of the total curvature caused by tropospheric refraction. These values apply when the refractive index at the surface is 1.000345, which is the approximate index over ocean areas at latitudes between 30 and 40 degrees north.[2] The amount of bending (and the index) will be less in more northerly latitudes and greater in more southerly latitudes - largely because of the difference in water vapor content of the atmosphere.

The assumption of an effective earth radius equal to four-thirds times true earth radius is frequently used for estimating the distance to the radio horizon but it is a compromise that is useful only for near-earth applications. Compared to the radius of the true earth, the effective "radio radius", k, varies with surface height and refractive index as shown in Table 2 (extracted from Reference 1).

Table 2

Surface Height (Above Sea Level)	Refractive Index	Effective Earth Radius (k)
0	1.000360	1.6
0	1.000340	1.5
700 ft.	1.000312	1.4
5,000 ft.	1.000250	1.25
10,000 ft.	1.000200	1.18
7 nm.	1.000060	1

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[1] "CRPL Exponential Reference Atmosphere," NBS Monograph 4, National Bureau of Standards, Oct. 29, 1959.

[2] "Climatic Charts and Data of the Radio Refractive Index for the United States and the World," NBS Monograph 22, National Bureau of Standards, Nov. 25, 1960.

A radio ray entering or leaving the earth's atmosphere at an angle such that it is tangent to the earth's surface cuts through all layers of the atmosphere and thus is subjected to a continually changing refractive index. One way to view this is to consider the radio ray as a straight line above an earth of continually changing effective radius. As illustrated in Figure 4, the true earth radius applies when the ray is above about 7 nm. By the time the ray has reached an altitude of 10,000 feet, the earth's effective radius has become 1.18. The effective radius continues to increase until it becomes about 1.5 at sea level (in the temperate zone).

Maximum Radio Distance. The distances covered by the radio ray that arrives at (or leaves) the earth at various angles of elevation and in atmospheres of various values of refractive index have been tabulated in Reference 1. Table 3 is based on this reference and shows the distances to the horizon from several altitudes of interest for a surface refractive index of 1.000345. The true earth distances (no bending) are also included.

Table 3

Altitude (Transmitter or Receiver)	Distance to Horizon in Nautical Miles — With Atmospheric Bending: Radio Path	With Atmospheric Bending: On Surface	No Bending: On Surface
7 nm	253	253	220
100 nm	886	871	820
345 nm	1630*	1560*	1480
Between Altitudes of	**Total Distance - Nautical Miles**		
7 & 100 nm	1139	1124	1040
7 & 345 nm	1883	1813	1700
100 & 345 nm (via a/c at 7 nm)	3022	2937	2740

*Extrapolated

The last line of the table represents the longest track, or path length, that could be seen from an aircraft at an altitude of 7 nm and applies only if the aircraft is directly under the path. However, since this "visibility" is greater than the distance covered by the spacevehicle during the communication period (2740 nm from Table 1), it appears possible to station the aircraft somewhat to the side of the spacevehicle path. This has the advantage of avoiding the need for an aircraft antenna that will follow an overhead pass. Also, the look angle, or angle between the roll axis of the spacevehicle and the transmission path, will be larger and the possibility of flame attenuation will be reduced.

The preceding paragraph carried the implication that transmission will be unimpaired when a radio path is tangent to the earth. However, with no earth clearance, free space transmission cannot be expected. The earth will intercept part of the radio wave and there will be losses that cannot be tolerated in a limited power system such as that in the spacevehicle. Even with a small amount of clearance there will be transmission difficulties due to destructive interference between the direct and surface-reflected radio rays. As the clearance increases, transmission will improve until the clearance approximates that for the first Fresnel zone, at which time the path loss may drop to about 6 db below that for free space. Of course, with a further increase in clearance (as the spacevehicle moves toward the aircraft), the path loss will increase again and then follow the familiar lobing pattern created by the alternate phasing in and phasing out of the direct and reflected radio rays.

At frequencies near 300 mc the first Fresnel zone clearance is in the order of 2,000 feet. To achieve this clearance the maximum surface distances between aircraft and spacevehicle are estimated from Reference 1 to be as shown in Table 4.

Table 4

Aircraft Altitude	Spacevehicle Altitude		Maximum Separation - nm Radio Path	On Surface
7 nm	100 nm		1100	1085
7 nm	345 nm		1830	1770
		Total	2930	2855

Thus, for an overhead pass, an aircraft at an altitude of 7 nm would be able to "see" a total of 2855 nm (on the surface) from the first (lowest) lobe of the radiation pattern in one direction to the first lobe in the opposite direction. This is 115 nm greater than the track of the spacevehicle during the desired nine and one-half minute recording period, and as estimated graphically in Figure 5, permits the aircraft to be stationed as much as 400 nm to the side of the burn path. The maximum surface distance for this situation (aircraft to spacevehicle at +3) is 1770 nm. The radio path length is about 1830 nm and the transmission system would have to overcome the corresponding path loss. With non-directional antennas, fading due to multi-path transmission would be expected.

4.3 Path Loss Variations

Multi-Path. The situation shown in Figure 5 for one aircraft would be satisfactory only if the communication link could tolerate the fading resulting from the interference between the direct and surface-reflected radio rays at low elevation angles. Since injection is expected to occur over the ocean (where, with two exceptions,* the reflection coefficient is nearly unity), radio transmission will experience deep fading unless the reflected ray can be cut off. At small angles above the horizon, very narrow antenna beams would be required to discriminate between the direct and reflected rays - narrower than are practical in an aircraft installation.

At this point, it will be assumed that the spacevehicle-aircraft radio systems have enough transmission margin to tolerate a fade of 6 db. This occurs when the voltage of the reflected ray is one-half that of the direct ray, thus leaving (at phase opposition) a net voltage of one-half that of the direct wave (down 6db).

An antenna discrimination of 6 db requires the angle between the reflected ray and the antenna axis to be somewhat more than half the antenna beamwidth as measured at the 3-db down points. As discussed later, the beamwidths of the S-band and VHF antennas on the aircraft may be in the order of 5 degrees and 25 degrees, respectively. The 6-db down angles from the centerline of the antennas will then be approximately 3 degrees and 15 degrees. For these minimum angles, the maximum surface distances between the aircraft (at 7 nm altitude) and the spacevehicle have been computed for several altitudes and are shown in Table 5.

Table 5

Spacevehicle Altitude in Nautical Miles	Limiting Surface Distances Between Aircraft and Spacevehicle - nm	
	S-band (3°)	VHF (15°)
100	860	510
138	1000	640
176	1125	745
345	1525	1125

The corresponding elevation angles of the antenna beam centerline above the horizon (at the limiting distances) are about 2.7 degrees for S-band and about 10 degrees for VHF. Obviously,

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*The exceptions apply to vertical polarization over a small range of elevation angles above the horizon, and to all polarizations when the sea is very rough.

the VHF radio links are controlling, and the following work on positioning aircraft will be based on these links. If, however, all the necessary information is transmitted by S-band and the VHF channels are not needed at this time, the maximum distance between the aircraft and the spacevehicle could be increased as indicated in Table 5. The full increase shown in the table cannot be realized because of the limitations of the radio transmission system. The maximum radio communication ranges are evaluated in Section 4.8.

The minimum elevation angles for the aircraft antennas have been chosen to reduce the effects of two-path propagation to an acceptable level. A maximum elevation angle should also be selected in order to simplify the antenna scanning problem. Some types of antennas, such as a large dish antenna mounted in the nose of an aircraft, or an electrically-scanned array installed on the side of an aircraft, may not be able to scan very high in a vertical plane. The maximum elevation angle for some types of electronically scanned antennas appears to be about 30 degrees, and this value has been used to establish the minimum offset of the aircraft from the path of the spacevehicle. This is shown in Figure 5, wherein the dotted line indicates the closest approach of the aircraft to the track of the spacevehicle without exceeding the 30-degree elevation angle.

With this information, plus the previously derived maximum distances associated with a 15-degree angle between the direct and reflected VHF radio rays, it is possible to establish the number and location of aircraft required to record signals from the spacevehicle for a specific injection path (not all possible paths). This has been done graphically,* and, as shown in Figure 5, two aircraft are necessary (not counting spare, or back-up, aircraft). One aircraft would be stationed at a point 480 nm along the surface track (from time equals -6.5 minutes) and 176 nm to the side. The second aircraft would be stationed 1550 nm along the track (from -6.5) and 235 nm to the side. It would not quite be able to "see" the spacecraft at the +3 point within the 15-degree limitation. As noted in Figure 5, it misses by about 75 miles, but this converts to only about one degree of elevation and is not a practical limitation. The radio distance to the +3 point would be about 1300 nm and this should be used to determine the maximum path loss.

Tropospheric Fading. If the line-of-sight from the aircraft to the spacevehicle is at least 10 degrees above the horizon,

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*Because of the changing altitude of the spacecraft, the solution involved a series of successive approximations.

the line-of-sight will always be more than 7 nm above the earth. Fading due to inhomogeneties in the atmosphere should be very small and only one db fading margin will be allowed. As discussed in the next paragraph, an additional decibel will be allowed for fading in the ionosphere. The total allowance for fading in the propagation medium is thus 2 db.

Ionospheric Effects. Refraction occurs in the ionosphere as well as the troposphere, but to a lesser extent. In this case the amount of bending of radio waves is a function of electron density, collision frequency, radio frequency, and the angle of elevation above the horizon. Although the refractive effects would have to be considered in tracking problems, they appear to be small enough to be ignored in communication problems - at least at VHF and higher frequencies.

The ionosphere, in combination with the earth's magnetic field, can cause a rotation of the plane of polarization of a radio wave (Faraday effect). The effect varies inversely with the square of the radio frequency and is small above about two gc. At VHF however, the effect is substantial, thus requiring the use of circular polarization or, alternately, plane polarization diversity in the aircraft.

Another effect occurring in the ionosphere is phase dispersion[3]; i.e., the phase shift across the RF signal band may not be linear with frequency. If two components of a modulated 100 mc carrier are separated by 100 kc, their phase relationship may be changed by the ionosphere, and at an elevation angle of 5 degrees, this can amount to 180 degrees (during daylight in the temperate zone). This effect also varies inversely with frequency. At 1000 mc, frequency components separated by 1 mc may find their phase relationship changed by 90 degrees. It appears, then, that if VHF is to be used at small angles of elevation, phase distortion should be expected unless the RF bandwidth is well below 100 kc. Thus, both phase dispersion and the previous multipath considerations suggest keeping the transmission path significantly above the horizon.

The ionosphere is composed of shifting layers of ionized gas, and it appears that this non-uniformity could result in transmission variation. Just what fading margin should be allowed is not known, but at VHF and higher frequencies only a small amount of fading should be expected. The

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[3]"Introduction to Space Communication Systems", McGraw-Hill, New York, 1963.

allowance made here is one db. When added to the allowance for tropospheric fading, the total margin for fading is two db.

Flame Attenuation. The general theory of signal attenuation in an exhaust flame suggests that the attenuation should be quite small when the fuel is a mixture of hydrogen and oxygen, which is the case for the S-IVB. In addition, the "look angle" (the angle between the roll axis of the spacevehicle and the radio path to the aircraft) for the geometry shown in Figure 5 would be greater than 15 degrees throughout the burn period, and hence would not pass through the region of highest ionization density in the plume. It is therefore assumed that the radio frequency loss due to the S-IVB exhaust during the injection burn will be negligible. There is support for this assumption in the experimental results reported for the Saturn SA-5 test flight,[4] but further verification is desirable.

It is understood that the fuel used for attitude control will also be a hydrogen-oxygen mixture, and hence attenuation due to this system should also be negligible.

4.4 Antennas

It is assumed here that the VHF and S-Band antennas on the Command Module are linearly polarized and have unity gain except for 3 db losses at some angles in the antenna patterns. A 3 db polarization loss is also assumed because the aircraft antennas must be circularly polarized in order to be able to receive a signal from the spacevehicle regardless of its attitude. The total loss will be more than 6 db unless the spacevehicle is provided with more than one antenna and these antennas are oriented in different directions. This is because of the null zones associated with any non-directional antenna; for example, in the direction of the axis of a whip or dipole type of antenna.

It is understood that a horn-type, linearly polarized antenna of 9 db gain will be associated with the S-Band radio equipment in the Instrumentation Unit. However, since the axis of the antenna beam is expected to be vertical, the radiation toward the horizon (and the aircraft) will be much reduced. In order to be useful, the gain cannot be much, if any, below unity at ±75 degrees from the center of the beam and this gain will be assumed. An angle of 150 degrees subtends the earth when the spacevehicle is at an altitude of 100 nm.

[4] "Radio Frequency Evaluation of SA-5 Vehicle," NASA MSFC Technical Memorandum X-53073, June 10, 1964.

The limited power in the spacevehicle, plus the considerable path loss at injection ranges, plus various equipment and fading losses, make it necessary to provide gain antennas on the aircraft for both VHF and S-band radio systems. The situation is such that the gains (and sizes) of these antennas should be as large as the structure and performance of the aircraft will permit.

It is assumed that the aircraft assigned to this mission will be C-135 jets and that they will permit the installation of a 6-foot dish antenna for S-band frequencies and an 8.5 x 8.5 foot antenna array for VHF. Because of its size, the latter would probably have to be mounted on the side of the aircraft. It follows, then, that the dish antenna should be mounted on the side of the aircraft, or, if installed elsewhere, it should be oriented in the same direction as the VHF array.

The gain and beamwidth of an antenna array are primarily dependent on its over-all size (in wavelengths). Secondarily, they depend on the number and spacing of the antenna elements that make up the array. Either a 3 x 3 or 4 x 4 element array could be used (with different spacings) to obtain a gain of about 15 db and an accompanying beamwidth of about 25 degrees. However, because of coupling effects, the 4 x 4 array is superior from a side lobe standpoint and has particular merit when the antenna beam is electronically scanned. If a 3 x 3 array is scanned 30 degrees off normal (from broadside), one of the side lobes will grow to the size of the main lobe and this decreases the array gain. In addition, the side lobe could point in the direction of the surface-reflected wave, thus increasing multi-path interference.

The simplest antenna element that will provide circular polarization is a pair of crossed dipoles and it will be assumed here. This should not be understood to rule out the possibility of crossed slot antennas, the radiation characteristics of which are similar to those of the dipoles. They would have the advantage of flush mounting, thus minimizing radome requirements. It would also be possible to use an array of helical antennas. Their principal advantage is that they are not as sensitive to frequency changes as are dipole and slot antennas and consequently would perform better at the extremes of the 216 to 300 MC range. Because of their length (about 2.5 feet for a 3-turn helix), they would require a deeper radome.
Both the S-band (dish) and VHF antenna must be able to scan in a vertical plane. The beam of the former could be swung

by mechanical movement of the feed, but, because of its size, the VHF array must be scanned electronically. The maximum practical scan angle appears to be about 30 degrees.

4.5 RF Bandwidth

The RF bandwidth required by a radio system depends on the highest frequency in the baseband, the method and degree of modulation, oscillator frequency drift, and, if there is relative motion between the transmitter and receiver, on the amount of Doppler shift. In systems having a narrow information band, the last two items may make it difficult to achieve a satisfactory signal-to-noise ratio. Such cases require automatic tracking of the carrier frequency.

The IF bandwidths of the several signals received from the spacevehicle are listed in Table 6.

Table 6

Radio Channel	IF Signal Bandwidth, kc.
VHF AM 3 kc Voice	6
VHF PCM/FM Telemetry at 51.2 kbps	77 (1)
VHF PCM/FM Telemetry at 72 kbps	108 (1)
VHF PAM/FM/FM IRIG TLM-Top ch. #18	225 (2)
S-Band in IU-PCM/FM Telemetry at 72 kbps	108 (1)
Unified S-Band in CSM	
Mode A - FM/PM Voice, and PCM/PM/PM Telemetry at 51.2 kbps	4810 (3)
Mode F - FM Emergency Voice	12 (4)

(1) Assumes IF bandwidth is 1.5 times bit rate

(2) Assumes top frequency in chan. 18 of 75.25 kc, and a modulation index of 0.5 for the VHF carrier.

(3) For top modulating frequency of 1.26 mc (voice channel frequency-modulated on 1.25 mc sub-carrier) and modulation index of 0.91, the Carson's Rule IF bandwidth = 4.81 mc.

(4) No sub-carrier is used. Modulation index of main carrier is one.

The allowances for changes in IF frequency due to Doppler shift and to oscillator drift are listed in Table 7. The oscillator stabilities are taken from IRIG standards; thus, actual equipment performance may be better than these figures indicate.

Table 7

Frequency Change Due to	Bandwidth Allowance - kc VHF (250mc)	S-band (2200mc)
Doppler Shift, Pos.	+6	+50
Doppler Shift, Neg.	-9	-80
Oscillator Drift		
Spacevehicle (Trans.)	±25	±110
Aircraft (Rec.)	±12	±22
Total	+43, -46	±182, -212

If the receiver are operated at a fixed frequency, that is, no tuning during the pass of the spacevehicle, the total IF bandwidths required are as given in Table 8.

Table 8

Radio Channel	I-F Bandwidth (kc) Required For Signal	Doppler Plus Osc. Drift	Total-Minimum For Recording
VHF 3 kc DSB Voice	6	89	95
VHF PCM/FM-51.2 kbps	77	89	166
VHF PCM/FM-72 kbps	108	89	192
VHF PAM/FM/FM	225	89	314
S-Band in IU	108	394	502
Unified S-Band in CSM			
Mode A - Overall	4810	394	5200(3)
1 Step of Demodulation(1)	1260	0(1)	1260
51.2 kbps TLM(2)	77		
3 kc FM Voice(2)	21		
Mode F - Emergency Voice	12		

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(1) Carrier tracking required for signal recovery.

(2) Bandwidth of signal about subcarrier on each side of main carrier. For TLM this is 1.5 x 51.2 = 77 kc; for voice, M = 2.5 and bandwidth is 6 (M+1) = 21 kc. The noise bandwidths are double these values, or 154 kc for telemetry, and 42 kc for voice.

(3) Bandwidth of front end of receiver - not for recording.

The allowances for Doppler shift and oscillator drift are substantial; radio system performance could be improved by the use of automatic tracking of the carrier, either in the aircraft or at the ground station analyzing the tapes. If carrier tracking is not employed in the aircraft, the pre-detection bandwidths should be at least as wide as the totals shown in Table 8. The following calculations will assume automatic carrier tracking will make it possible to use the narrower IF bandwidths at the ground stations.

4.6 RF Losses

The radio frequency losses (other than those due to free space) that must be considered in solving the transmission problem are listed in Table 9, along with their assumed values. The equipment losses for the CSM systems as listed in North American Aviation document SID 62-1452[5] have been used as a guide for the spacevehicle losses. The various fixed RF losses for the aircraft receiving equipment have been lumped as indicated by the bracketed quantities.

The table is divided into two sections: losses which must be considered fixed, and losses which are variable. The latter are segregated to facilitate transmission calculations for two conditions:

1. Assuming that all the variable losses reach their maximum values simultaneously and must be added arithmetically. This is a conservative and probably pessimistic case.

2. Assuming the variable losses are randomly related, in which case the probable total of the variable losses is more nearly an RSS value.

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[5] "Apollo Spacecraft - GOSS Communications Circuit Margins," North American Aviation Document SID 62-1452, reissued August 2, 1963.

Table 9

RF Loss Due To	RF Losses (DB) Including Fading: VHF Tran. (S/V)	VHF Rec. (A/C)	S-Band (CSM) Tran. (S/V)	S-Band (CSM) Rec. (A/C)	S-Band (IU) Tran. (S/V)	S-Band (IU) Rec. (A/C)
Fixed Losses						
Cable	1.5	2.0	1.3	1.0	3.0	1.0
Mismatch and Connectors	1.3		0.7		0.7	
Diplexer or Multi-Coupler	1.7		1.0			
Polarization		3.0		3.0		3.0
Total Fixed Losses	4.5	5.0	3.0	4.0	3.7	4.0
Variable Losses						
Antenna Pattern	3.0		3.0		0	
Antenna Pointing		0.5		0.5		0.5
Fading		2.0		2.0		2.0
Multi-Path		6.0				
Contingencies	1.0	1.0	1.0	1.0	1.0	1.0
Total Variable Losses (Arithmetic Addition)	4.0	9.5	4.0	3.5	1.0	3.5
Total Variable Losses (RSS Addition)	3.1	6.4	3.1	2.3	1.0	2.3
Total Losses						
Arithmetic Addition	23		14.5		12.2	
RSS Addition	16.7		10.9		10.2	

4.7 Receiver Noise

The noise temperature of a radio system referred to the input of the receiver can be computed from the formula

$$T_{sys} = \frac{T_S}{L} + \frac{T_A}{L} + T_o \frac{(L-1)}{L} + T_R$$

where

	Assumed to be VHF	Assumed to be S-Band
T_S = Sky temperature (main antenna beam), K°	400	25
T_A = Antenna temperature (side and back lobes), K°	40	30
T_R = Receiver temperature, K°	440	170
T_o = Temperature of transmission line, K°	290	290
L = Loss in transmission line (expressed as a ratio)	1.58	1.26
T_{sys} =	825°	275°

The noise power density for these two situations is

$$N_V = KT_{sys} = 1.38(10)^{-23}(825) = -199.5 \text{ dbw for VHF}$$

and

$$N_S = KT_{sys} = 1.38(10)^{-23}(275) = -204.2 \text{ dbw for S-Band}$$

where

K is Boltzmann's constant.

The receiver noise temperatures are based on receiver noise figures of 4 db and 2 db, respectively, for VHF and S-Band equipment. Although receivers with lower noise figures are within the state of the art, they would be of doubtful benefit because of the noise environment in an aircraft. Even the noise figures of 4 and 2 db will not be controlling unless suitable measures are taken to control other noise sources such as electrical machinery, precipitation static, and spurious radiations from on-board transmitters.

The noise power in the several bandwidths discussed in Section 4.5 can now be determined and they are given in Table 10. These values apply to the signal bandwidth only and not to the receiver bandwidths which, for VHF, must include an allowance for Doppler shift and oscillator drift.

Table 10

Radio Channel	Noise Power in IF Signal Bandwidths - dbw
VHF 3 kc DSB Voice	-161.7
VHF PCM/FM - 51.2 kbps	-150.6
VHF PCM/FM - 72 kbps	-149.2
VHF PAM/FM/FM	-146.0
S-Band (IU)	-153.9
Unified S-Band (CSM)	
Mode A - Overall	-137.0
1 Step of Demodulation[1]	
PCM/PM/PM 51.2 TLM	-152.3
FM/PM Voice	-158.0
Mode F - Emerg. Voice	-163.4

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[1] Carrier Tracking required.

4.8 Estimated Maximum Path Length

Only the carrier-to-noise ratios required in the IF bands are now needed to compute the allowable path loss in each of the links. These ratios, for the VHF links, have been included in Table 11 along with the other parameters. The differences between the plus and minus values in each column represent the maximum path losses that can be tolerated without exceeding the specified error rate or voice circuit signal-to-noise ratio. The algebraic signs merely indicate the effect of the various items on the allowable path loss.

With a single monitoring aircraft, the required radio range is 1830 nm at 3 minutes after the end of burn, and this can be met only by the voice circuit, and then only if the variable losses add at random. With two aircraft (using minimum elevation angles of 10 degrees), the required radio range is 1300 nm, and for random addition of the variable losses, this can be met by both the voice circuit and the 72 kbps telemetry channel. The other two telemetry circuits come close to meeting the maximum range objective (within about a db). Thus, it appears that the injection interval could be covered fairly adequately, even though transmission during the last few hundred miles of the post-burn period might be subject to slightly more fading than assumed.

The last line of Table 11 shows the maximum path lengths that could be expected. It is assumed here that the variable RF losses have been over-estimated and actually may not exist at all, thus leaving only the fixed losses shown in Table 9.

Table 11

VHF PATH LENGTH CALCULATIONS

	3 kc Voice	PCM/FM 51 kbps	PCM/FM 72 kbps	PAM/FM/FM
Transmitter Power-DBW	7.0 +	10.0 +	13.0 +	13.0 +
RF Losses, Incl. Fading				
Arithmetic Addition	23.0 -	23.0 -	23.0 -	23.0 -
RSS Addition	16.7 -	16.7 -	16.7 -	16.7 -
Rec Antenna Gain	15.0 +	15.0 +	15.0 +	15.0 +
IF Noise(1)	161.7 +	150.6 +	149.2 +	146.0 +
Required C/N Ratio	10(2) -	13(3) -	13(3) -	11 -
Net Allowable Path Loss, db:				
Arithmetic Addition of RF losses	150.7	139.6	141.2	140.0
RSS Addition	157.0	145.9	147.5	146.3
Approx. Freq., mc	300	240	240	240
Max. Path Length, nm:				
Arithmetic Addition of Losses	1480	515	615	545
RSS Addition	3060	1060	1270	1100
No Variable Losses(4)	7000	2430	2910	2540

(1) Extra bandwidth for Doppler shift and oscillator drift assumed to be eliminated by carrier tracking of the recorded signals.

(2) This is based on a required audio rms speech-to-rms noise ratio of 10 db and a modulation loss of 3 db (70 percent modulation).

(3) Estimated ratio for one bit error in $(10)^5$ bits with coherent detection.

(4) If there were no variable losses (fading, antenna pattern variations, etc.), the maximum path lengths would be as shown.

The path loss calculations for the S-band links are shown in Table 12. Here, it is necessary to know the modulation indices of the sub-carriers in addition to the required carrier-to-noise ratios. These indices have been taken from Reference 5.

The maximum path lengths derived in Table 12 show that two aircraft can cover the injection period if the RF losses add on a random basis - a probable situation. However, this conclusion is based on the assumption that the first detector (a phase demodulator) in the Unified S-band receiver has no pronounced threshold. Rather, because of the low modulation indices, it performs more like an AM system and does not "break" at low carrier-to-noise ratios. There is substantiation for this view in North American Aviation Document SID-63-1043[6]. If this should be incorrect, and if a threshold does occur at a ratio of about 8 db (main carrier power to IF noise power), the first detector would be operating below threshold, thus vitiating the results in Table 12.

An alternate plan would be to avoid the conventional first detector (with its very wide noise band) and filter out specific signal bands of interest for demodulation. For example, one of the first order sidebands of the voice subcarrier (at 1.25 mc ± 10.5 kc) could be filtered from the broad IF band and demodulated in one step instead of two.

Path length calculations for mode B-1 of the Unified S-Band system from the CSM have not been included in Table 12. This mode differs from mode A in that it includes a pseudo-random code ranging signal in addition to the voice and telemetry signals. The ranging signal is of no direct interest to the aircraft, and presumably would be present on the down link only if the spacevehicle were also in view of a ship or land tracking station during some portion of the 9-1/2 minute period that the aircraft is in contact with the spacevehicle. The ranging

[6] "Second Interim Report Apollo Modulation Technique Study", North American Aviation Document SID-63-1043, September 3, 1963.

Table 12

S-BAND (2.3 kmc) PATH LENGTH CALCULATIONS

	Unified S-Band in CSM			S-Band in IU
	Mode A		Mode F	
	3 kc Voice	PCM/PM 51 kbps	Emergency Voice (FM)	PCM/FM 72 kbps
Transmitter Power, dbw	13.0 +	13.0 +	-7.0 (1) -	13.0 +
RF Losses, Incl. Fading				
Arithmetic Addition	14.5 -	14.5 -	14.5 -	12.2 -
RSS Addition	10.9 -	10.9 -	10.9 -	10.2 -
Losses - Modulation (2)	8.6 -	4.7 -	0	0
Rec. Antenna Gain	30.0 +	30.0 +	30.0 +	30.0 +
IF Noise	158.0 +	152.3 +	163.4 +	153.9 +
Required C/N Ratio	8 (3) -	11.5 (4) -	7.0 -	13.0 -
Net Allowable Path Loss, db:				
Arithmetic Addition	169.9	164.6	164.9	171.7
RSS Addition	173.5	168.2	168.5	173.7
Max. Path Length, nm:				
Arithmetic Addition	1750	950	990	2170
RSS Addition	2660	1450	1500	2730
No Variable Losses	4180	2280	2360	3640

(1) Equals 200 milliwatts. Assumes loss of power amplifier.

(2) Modulation indices for telemetry and voice subcarriers are $M_1 = 1.25$ and $M_2 = 0.91$, respectively. The modulation loss for telemetry is

$$2\,J_0{}^2(M_2)(J_1)^2(M_1) = 2(.803)^2(.511)^2 = .337 = -4.7 \text{ db}$$

and for voice it is

$$2(J_0)^2(M_1)(J_1)^2(M_2) = 2(.645)^2(.409)^2 = .139 = -8.6 \text{ db}$$

(3) This is the FM threshold for a deviation ratio of 2.5. The threshold occurs at about 10 db when the noise is measured in twice the baseband width (6 kc).

(4) For a bit error rate of one in $(10)^5$ bits.

signal would originate at a ship or land station, either as a separate signal in "up"-mode 1-A, or multiplexed with voice, data, or both in up-modes 1-D, 1-E, or 1-F, respectively. Regardless of which up mode is used, the ranging signal reaching the CSM would be translated in frequency and retransmitted as part of down-link mode B-1. However, there is a difference in the distribution of power among the ranging, voice, and telemetry signals on the down link, depending on which up-link mode is used.

Reference 5 repprts calculations which show the relative transmission margins for the down-link voice and telemetry signals when each of the four up-link options is used. Based on these calculations, it appears that the allowable path loss for mode B-1 would be from one to 5.5 db less than the values given for mode A in Table 12. The worst case (5.5 db less allowable path loss) occurs when ranging signals only are transmitted on the up link (mode 1-A). This represents almost a 2:1 reduction in transmission range from the values in Table 12, and hence the 1-A up-link mode ought not to be used if it can be avoided during the period in question. If one of the other three up-link modes involving ranging are in use, the transmission performance of the down link telemetry and voice channels would be degraded by no more than about 1.5 db relative to their performance in mode A.

5. NUMBER AND DEPLOYMENT OF AIRCRAFT

5.1 Assumptions

Based on the geometry shown in Figure 5 for the case of two aircraft covering the 9.5-minute interval, an analysis has been made of the number of aircraft that would be required to cover the injection opportunities on a single day. Assumptions used in this analysis are as follows:

1. Launch azimuth is limited to the region 72° to 108°, based on Reference 6.

2. The maximum spread of launch azimuths on any single day will not exceed 26° (Reference 6).

3. Ground tracks of the first three orbits for launch azimuths of 72° and 108° are as shown in Figure 6. These are taken from Reference 7. Also shown are loci of injection opportunities throughout a lunar month, referred to the maximum northern and southern declinations of the Moon ("Northern Lunstice" and "Southern Lunstice"). These loci refer to the start of the injection burn.

4. Injection may occur as early as the first orbit in the Pacific Ocean and as late as the end of the third orbit.

5. Aircraft can maintain a speed of 450 knots.*

6. Aircraft are kept informed, with negligible delay, of the progress of the launch and of any subsequent events affecting the location and time of injection.

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[6] "Appollo Operational Nominal Trajectory Ground Rules," MSC Internal Note No. 64-DM-4 by NASA-Manned Spacecraft Center, March 14, 1964.

[7] "A Study of Instrumentation Ship Requirements for the Apollo Program", Bellcomm, Inc., September 14, 1963.

*Although the cruising speed of the C-135 aircraft is about 600 knots, it is assumed here that a combination of head winds, air resistance of large radomes, and maximum loading of the aircraft (for a 7 nm altitude) may limit the maximum dependable ground speed to 450 knots.

When these assumptions are applied in conjunction with the ground tracks shown on Figure 6, it appears that the most demanding coverage requirement on any one day is in the vicinity of the Pacific Ocean equator. This area has therefore been chosen to illustrate aircraft coverage concepts and capabilities. More specifically, the injection burn opportunities on the day corresponding to the spacecraft's arrival at the Moon six days after Northern Lunstice (NL + 6) have been selected for study. The launch azimuth limits have been taken as 77° to 103°, which is a 26° spread centered around 90°*, and which appears to pose the greatest coverage requirement of any 26° spread on the chosen day.

The region selected for analysis is indicated by the cross-hatched area on Figure 6. The spread of tracks for the first orbit, corresponding to launch azimuths of 77° to 103°, is shown in magnified form in Figure 7. Contours are indicated for the start and end of the injection burn, and for one minute before and three minutes after the burn period. The locations of a number of islands which might serve as bases for aircraft are also indicated.

Aircraft coverage has been analyzed for three possible operational plans, as follows:

1. Injection on any of the first three orbits;

2. Injection on either the first or second orbit;

3. Injection on either the second or third orbit.

Implicit in the second and third plans is an assumption that the choice between them would be made well enough in advance of the earliest launch time to permit optimum deployment of aircraft. If it is expected that this decision would not be made until nearly the time of launch, aircraft

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*The tracks for 90° launch azimuth are not shown on Figure 6. They would fall approximately midway between the tracks for 72° and 108°.

coverage would have to be scheduled in approximately the same manner as for the first plan in order to cover the possibility of choosing either the second or third options.

5.2 Injection on Any of First Three Orbits

The basic pattern developed to cover injection opportunities on any of the first three orbits for a given launch azimuth is illustrated in Figure 8. Ground tracks are shown for a launch azimuth of 77°. Successive tracks are shifted westward by the amount of the earth's rotation during one orbit of the spacecraft, approximately 1-1/2 hours. Thus, at the equator, the tracks are moved westward approximately 1350 nm from one orbit to the next. With the surface coverages for two aircraft along the burn path, as indicated earlier in Figure 5, it is seen that four aircraft can cover the three injection opportunities. To accomplish this, aircraft #2 must cover the early part of a first orbit injection and the latter part of a second orbit injection. There is adequate time for this aircraft to move between its indicated positions for these two orbits. Similarly, aircraft #3 can cover the early portion of a second orbit injection and the latter part of a third orbit injection. Aircraft 1 and 4 each have only one assignment in this situation.

It might be questioned whether or not two aircraft would be adequate to cover the situation represented in Figure 8, one covering the early part of the injection on each orbit, the second covering the latter part on each orbit. It can be demonstrated that this is not possible when the aircraft speed is assumed limited to 450 knots. Aircraft #1, for example, would require slightly over 2-1/2 hours to move from its orbit #1 position to the position required for orbit #2, whereas there is only about 1-1/2 hours available.

<u>Effect of Launch Delay</u>. Assume now that the launch is held. As it is delayed, the desired launch azimuth changes approximately as shown in Figure 9 (adapted from Figure 4-1 of Reference 7). All potential injection burn tracks then shift westward, with the net effect that the total area over which injection can occur is greatly increased. This is illustrated by the tracks for the extreme launch azimuths in Figure 6. As will be seen, the effect of launch delay is to increase the number of aircraft from four to five.

When the spread of 26° in launch azimuth (from 77° to 103°) is comined with the three injection opportunities for each launch azimuth, the pattern of injection burn tracks and desired aircraft movement becomes rather complex, and it is confusing to try to show the entire pattern on one chart. An example of the coverage capability of one aircraft (aircraft #2 in the nomenclature adopted here) is given in Figure 10. In this illustration, the aircraft is assumed initially stationed at the point "St" at the time the launch window is opened. The dashed lines indicate the progress of the aircraft during its mission. Numerals above a line indicate the time available, in hours and minutes, to move from the starting point or a subsequent station to the next indicated station. Numerals below a dashed line indicate the time required for the movement, at a speed of 450 knots. Approximate total mission times can be gotten by adding the appropriate times along successive segments from the assumed departure base (Canton Is. is indicated in this case) to a return base.

The point "St" on Figure 10 is one hour's flight time west of the position that the aircraft should occupy if launch occurs at the opening of the launch window and injection occurs on the first orbit. One hour is approximately the time required for the Apollo spacecraft to travel from Cape Kennedy to this first injection position. If injection does not occur at this first opportunity, the aircraft has 1-1/2 hours to fly to the position indicated for covering the latter portion of the second orbit injection. Actually, the latter movement can be accomplished in only about 44 minutes. If the injection does not occur on the second orbit, the aircraft is of no further use on this day.

The movement just described applies when launch occurs at the opening of the launch window, $t = 0$, and the launch azimuth is 77°. Assume, now, that the launch is delayed. As soon as the aircraft is informed of this fact, it should start flying westward along the dashed line from the point "St". With the passage of time from $t = 0$, the required launch azimuth also changes (see Figure 9) and the potential injection positions move westward at a rate approximately twice that of the aircraft. If the launch occurs at any time up to $t = 1$ hr., 45 minutes, the relative movements of the aircraft and the injection tracks are such that the aircraft has time to cover the early part of a first orbit injection or, subsequently, the latter part of a second orbit injection. The launch azimuth at $t = 1:45$ would be about 90°.

If launch is delayed beyond t = 1:45, aircraft #2 can no longer keep up with the westward movement of the injection tracks. However, as may be seen from Figure 10, this aircraft's position at t = 1:45 is still some distance west of the position required to cover the latter part of a first orbit injection. (Aircraft #1 has carried this assignment for launch azimuths up to 90°, and in fact is able to continue doing so for launches up to about 92° azimuth before it is over-hauled by the westward movement of the injection tracks.) At about t = 1:45, assuming the launch is still being held, aircraft #2's assignment should be changed to take over the latter part of a first orbit injection. Its flight path should now be altered as shown on Figure 10, that is, it should begin heading toward the final position for a launch azimuth of 103°. From any point on this path, aircraft #2 can reach the desired position for covering the latter part of a first orbit injection, for launch azimuths between 92° and 103°.

It may be noted that if the aircraft were not initially stationed west of the first orbit injection track in "anticipation" of a delayed launch, it would be able to cover only a relatively narrow spread of possible launch azimuths before being overtaken by the westward movement of the potential injection positions.

The deployment of other aircraft has been worked out in a similar fashion. A summary of the coverage provided by each is given in Table 13. Also listed are suggested departure and return bases for each aircraft, and the approximate maximum mission times that would result if these bases were used.

5.3 Injection Limited to First or Second Orbit

Assuming it can be determined well in advance of the scheduled launch time that injection will occur on either the first or second orbits, it can be seen from Table 13 that four aircraft can provide the necessary coverage. Their assignments would be identical to those listed in the table for orbits 1 and 2.

It should be emphasized that the smaller number of aircraft required under this plan and under the following plan is possible only if the decision regarding the injection opportunities is made sufficiently early to allow deployment of the aircraft to their proper departure bases.

5.4 Injection Limited to Second or Third Orbit

When injection is to be restricted to the second or third orbits, there is approximately a 1-1/2 hour time advantage available for moving aircraft to their initial assignments, relative to the case when a first orbit injection must also be covered. This is enough to reduce the required number of aircraft to three, as indicated in the top half of Table 14. However, some of the maximum mission times can approach 10 hours when only three aircraft are used. The bottom half of Table 14 indicates the assignments and maximum mission times that would apply if four aircraft were used instead of three.

5.5 Departure and Return Bases for Aircraft

As is evident from the illustration of Figure 10 and the data in Tables 13 and 14, an extremely important factor in total mission time is the availability of suitable takeoff and landing points. If operations were restricted to the larger, well-developed bases like Hawaii and Guam, some of the required mission times almost surely would be greater than the capability of C-135 type jet aircraft. In general, the bases indicated in Tables 13 and 14 have been selected to require minimum time to reach initial station assignments, but it is not known whether all the bases listed can accommodate jet aircraft. Preferred return bases have been chosen as those where good communication facilities to the U.S. should be available. Since these are in many cases several hours flight time from an aircraft's coverage assignment, it might be considered preferable to land at a base having poorer communication facilities in order to shorten the total flight time.

5.6 Coverage on Successive Days

If an Apollo launch is held from one day to the next, the injection opportunities move northeastward along the parking orbit tracks as indicated on Figure 6. The spread in latitude between the loci of injection burns from day to day becomes progressively smaller, while the spread in longitude covered by each locus is relatively constant. Furthermore, there is slightly more time between launch and the first injection opportunity during which to move aircraft. These are the bases for the earlier statement that the coverage requirements near the equator appear to be the most demanding. It follows that the aircraft requirements on other days of the month probably would be no greater than on the day chosen for analysis, NL + 6. However, it is felt that a more detailed study of the coverage on several other days during the month eventually would be worthwhile to confirm this conclusion, and in any event such a study is needed to determine the specific aircraft deployment for each day. In conducting such a study, one should take into account the following factors:

1. The launch azimuths appropriate to a particular day;

2. Availability of suitable air bases in the area under consideration for a given day (conceivably, additional aircraft might be needed on some days to reduce mission times to acceptable lengths);

3. Time available to move aircraft from one base to another on successive days;

4. Supplementary coverage that might be provided by land stations or ships.

Table 13

COVERAGE PROVIDED BY AIRCRAFT FOR INJECTION OVER PACIFIC

ON NL + 6 ON ANY OF FIRST THREE ORBITS

	Launch Azimuths Covered-Degrees								
	Orbit No. 1		Orbit No. 2		Orbit No. 3				Approximate
Aircraft	Start	End	Start	End	Start	End	Departure Base	Return Base	Max. Mission Time, Hrs.
#1		77-92					Honolulu	Honolulu	8-1/2
#2	77-90	92-103		77-90			Canton	Hon. or Guam	8-1/2
#3	90-103		77-90	90-103		77-90	Kwajalein	Guam	8-1/4
#4			90-103		77-90	90-103	Guam	Guam or Man.	7-3/4
#5					90-103		Manila	Manila	7-1/4

Table 14

COVERAGE PROVIDED BY AIRCRAFT FOR INJECTION OVER PACIFIC
ON NL + 6 ON SECOND AND THIRD ORBITS ONLY

Aircraft	Launch Azimuths Covered-Degrees: Orbit No. 2 Start	Orbit No. 2 End	Orbit No. 3 Start	Orbit No. 3 End	Departure Base	Return Base	Approximate Max. Mission Time, Hrs.
	Coverage by 3 Aircraft						
#1		77-103			Kwajalein	Hon. or Guam	8-1/4
#2	77-103			77-103	Guadalcanal	Guam or Man.	9-1/2
#3			77-103		Pt. Moresby	Guam or Man.	9-1/2
	Coverage by 4 Aircraft						
#1		77-90			Kwajalein	Hon. or Guam	7-3/4
#2	77-90	90-103		77-90	Kwajalein	Guam	7-3/4
#3	90-103		77-90	90-103	Guam	Guam or Man.	7-1/2
#4			90-103		Manila	Manila	8-1/4

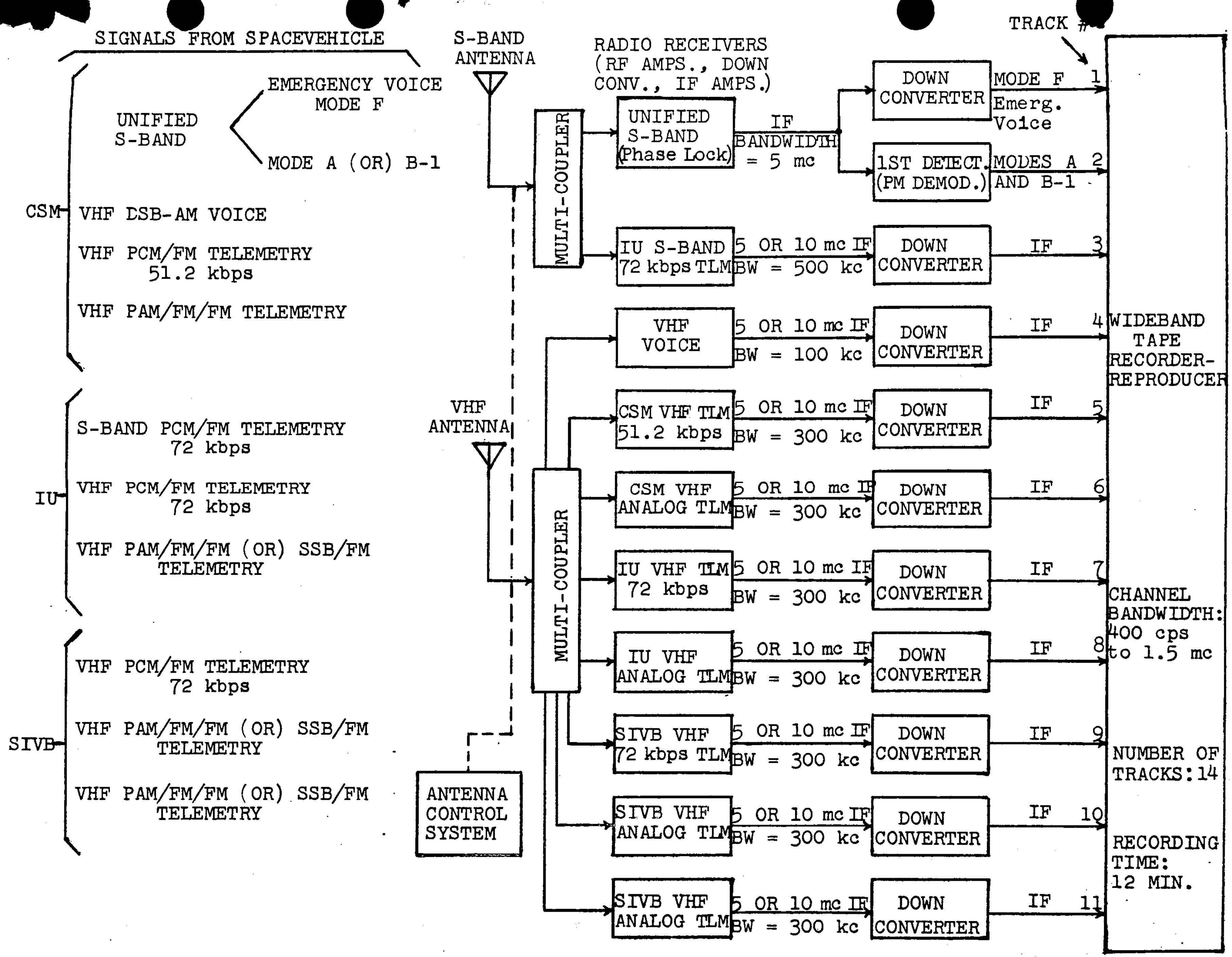


FIG. 1 - BLOCK DIAGRAM OF AIRCRAFT RECORDING SYSTEM

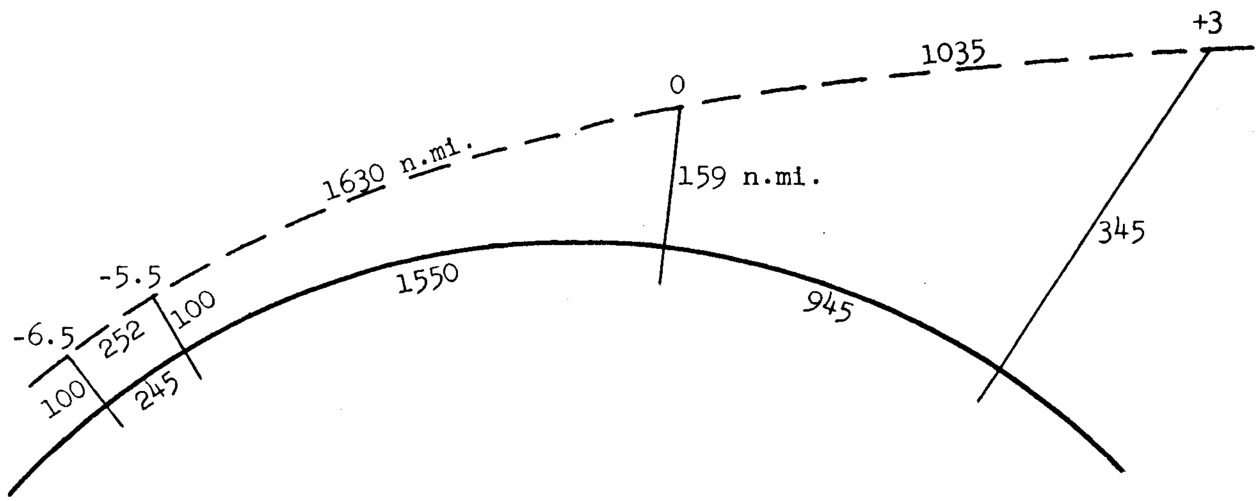


FIG. 2 - PATH OF SPACEVEHICLE

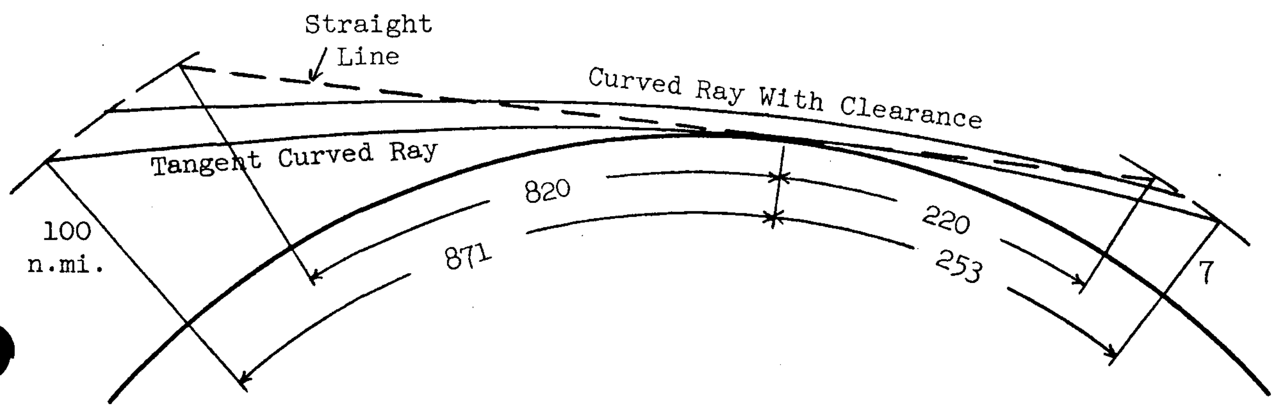


FIG. 3 - ADDITIONAL DISTANCE DUE TO BENDING
(n=1.000345)

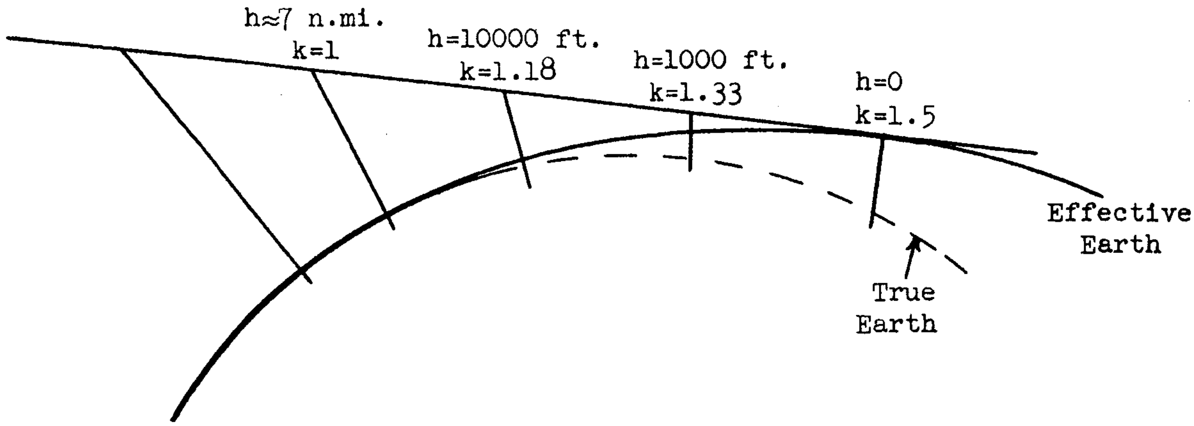
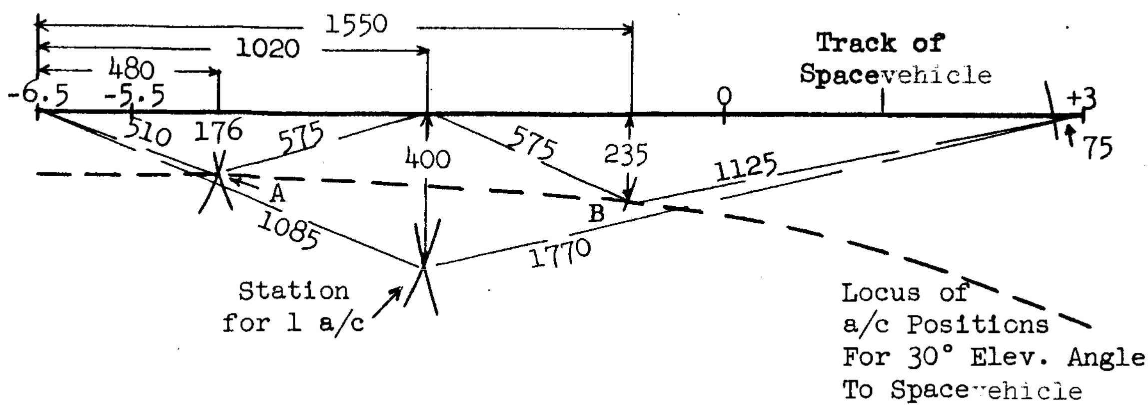


FIG. 4 - EFFECT OF ALTITUDE ON k FACTOR



To

FIG. 5 - SURFACE DISTANCES BETWEEN AIRCRAFT AND SPACEVEHICLE
A AND B INDICATE STATIONS FOR 2 AIRCRAFT

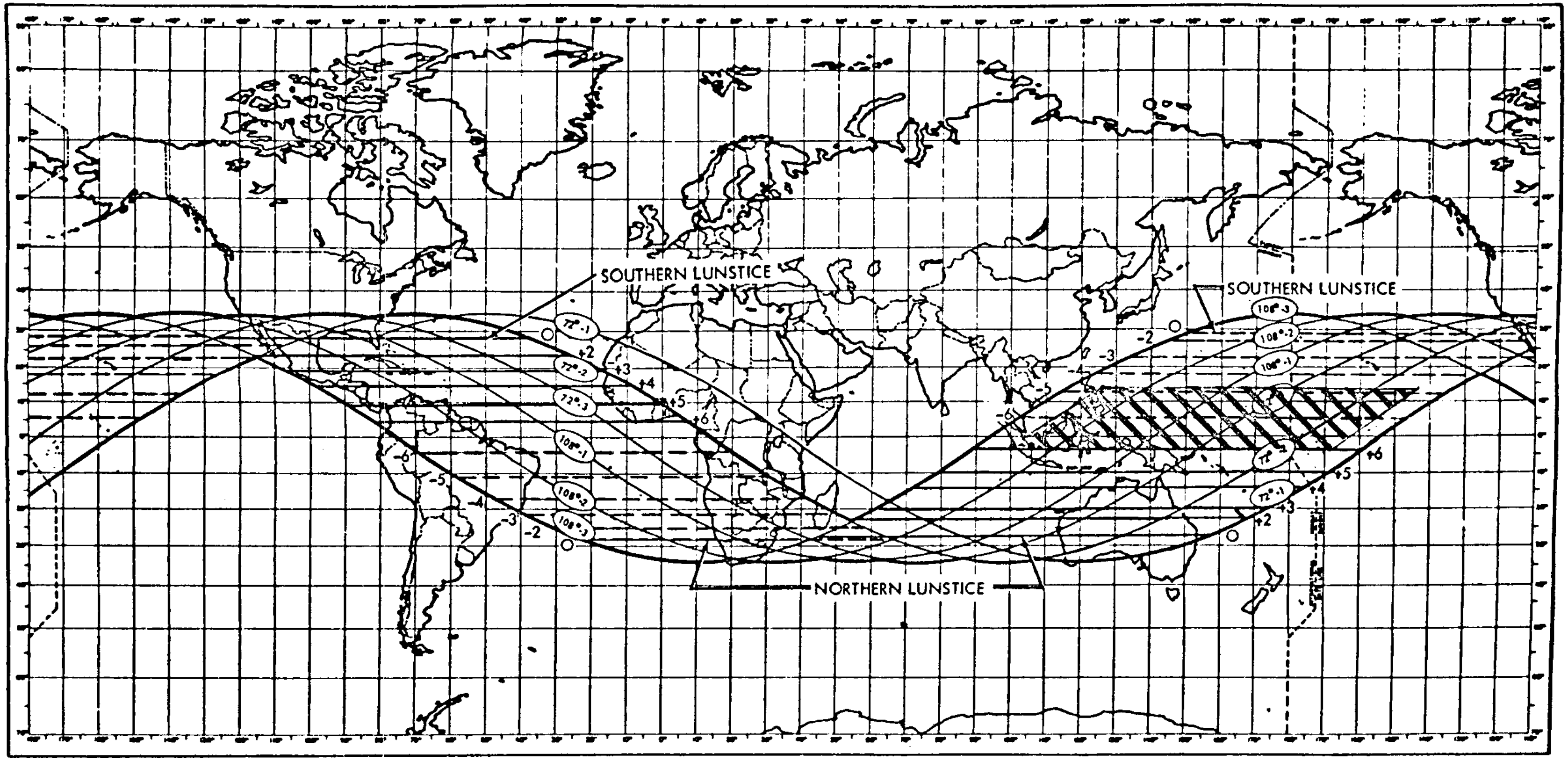


FIG. 6 – LOCI OF APOLLO INJECTION OPPORTUNITIES FOR DAYS FROM MAXIMUM LUNAR DECLINATION

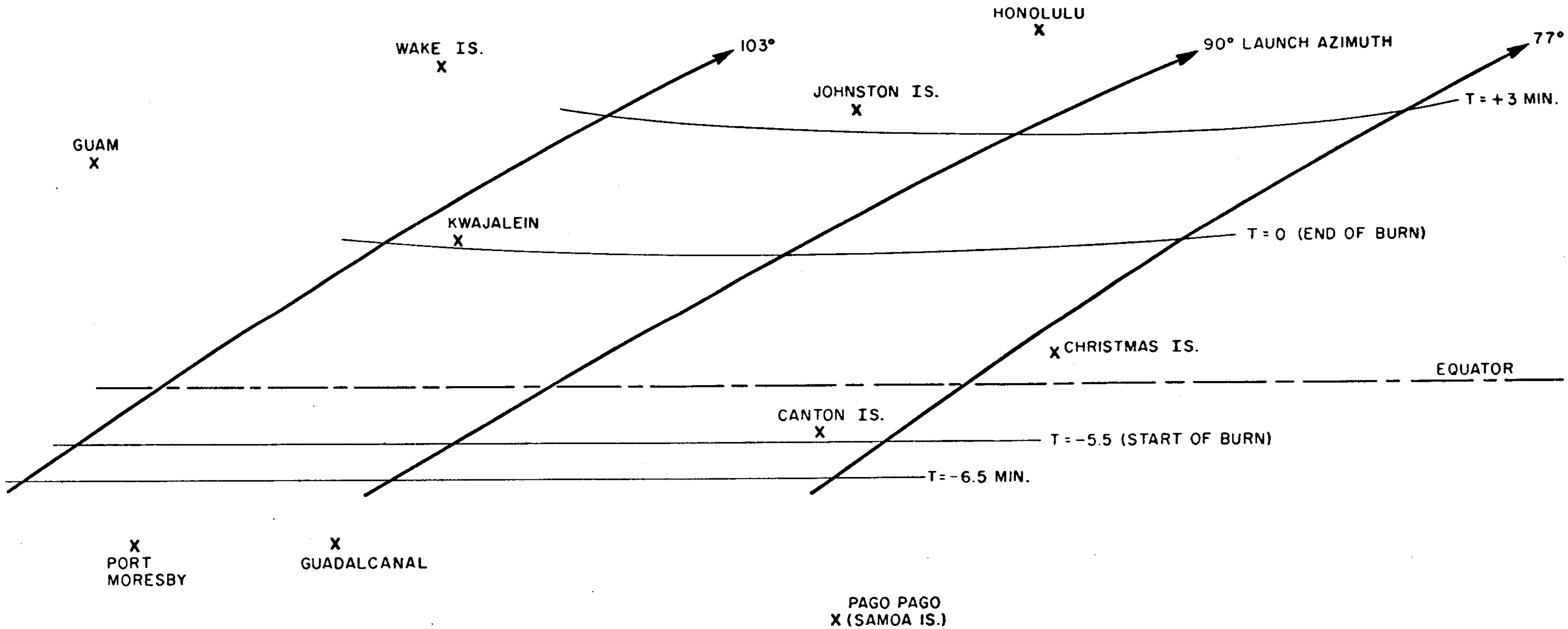


FIGURE 7

APOLLO INJECTION BURN TRACKS
FOR NL+6

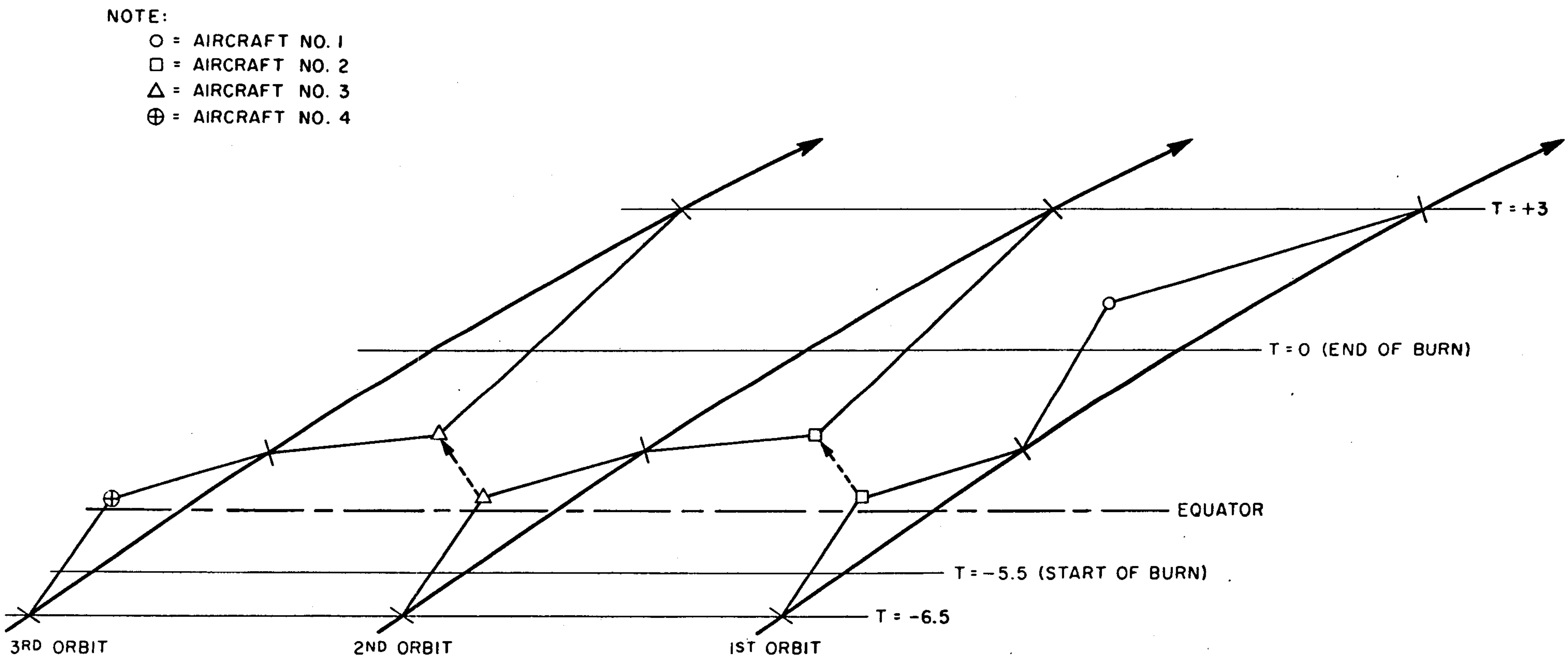


FIGURE 8

BASIC PATTERN FOR COVERAGE OF SUCCESSIVE INJECTION OPPORTUNITIES, ONE LAUNCH AZIMUTH (77° LAUNCH USED FOR ILLUSTRATION)

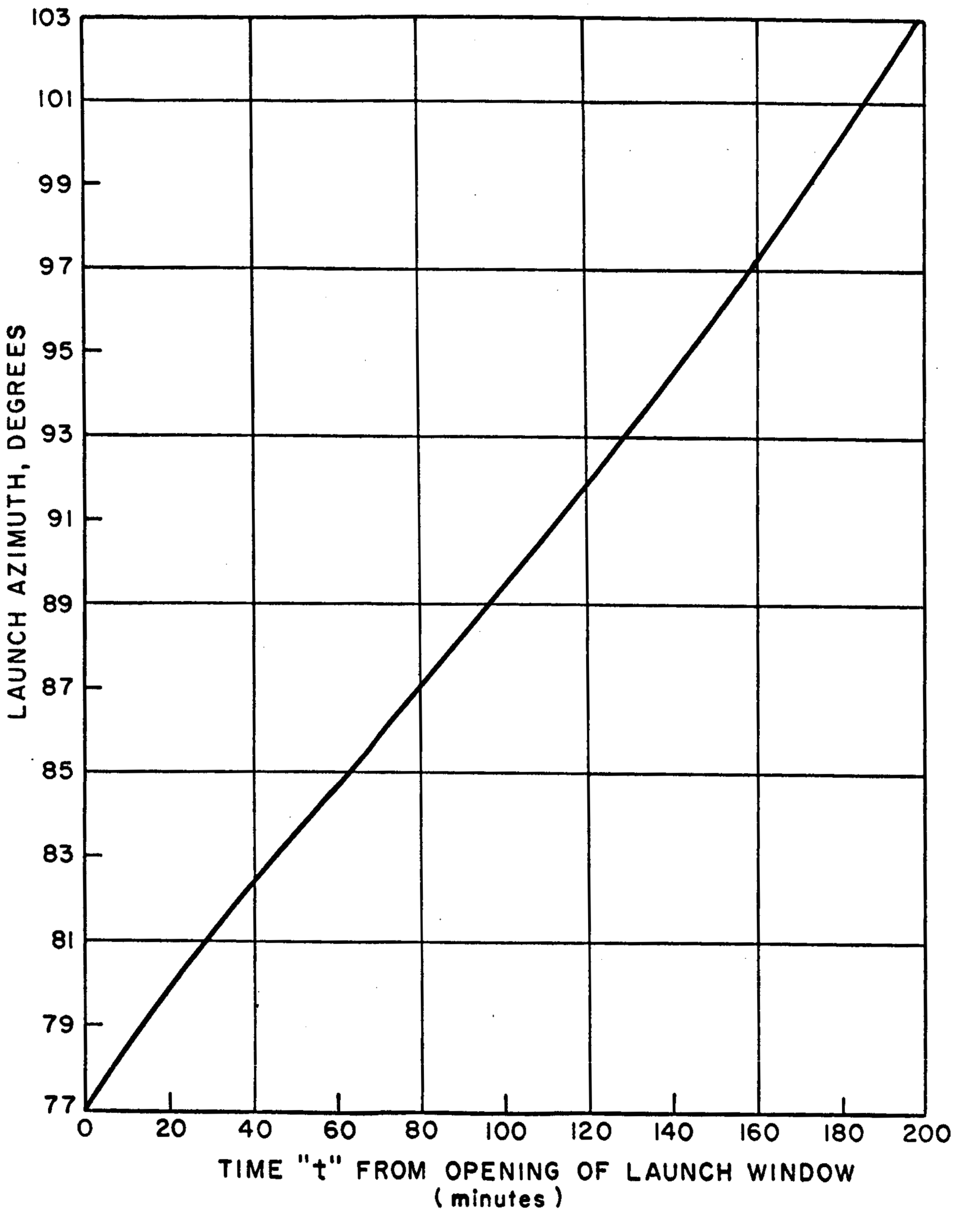


FIGURE 9

LAUNCH AZIMUTH VS TIME
FROM OPENING OF LAUNCH WINDOW

NOTES:

1. "□" INDICATES AIRCRAFT POSITIONS TO COVER DESIGNATED S/V TRACKS
2. "St" INDICATES STARTING POSITION FOR AIRCRAFT AT TIME "t" ("t = 0" CORRESPONDS TO OPENING OF LAUNCH WINDOW)
3. DASHED LINES INDICATE AIRCRAFT FLIGHT TRACKS
4. NUMBERS ABOVE AIRCRAFT TRACKS INDICATE TIME AVAILABLE FOR AIRCRAFT MOVEMENT (HOURS: MINUTES)
5. NUMBERS BELOW AIRCRAFT TRACKS INDICATE TIME REQUIRED FOR AIRCRAFT MOVEMENT, AT 450 KNOTS

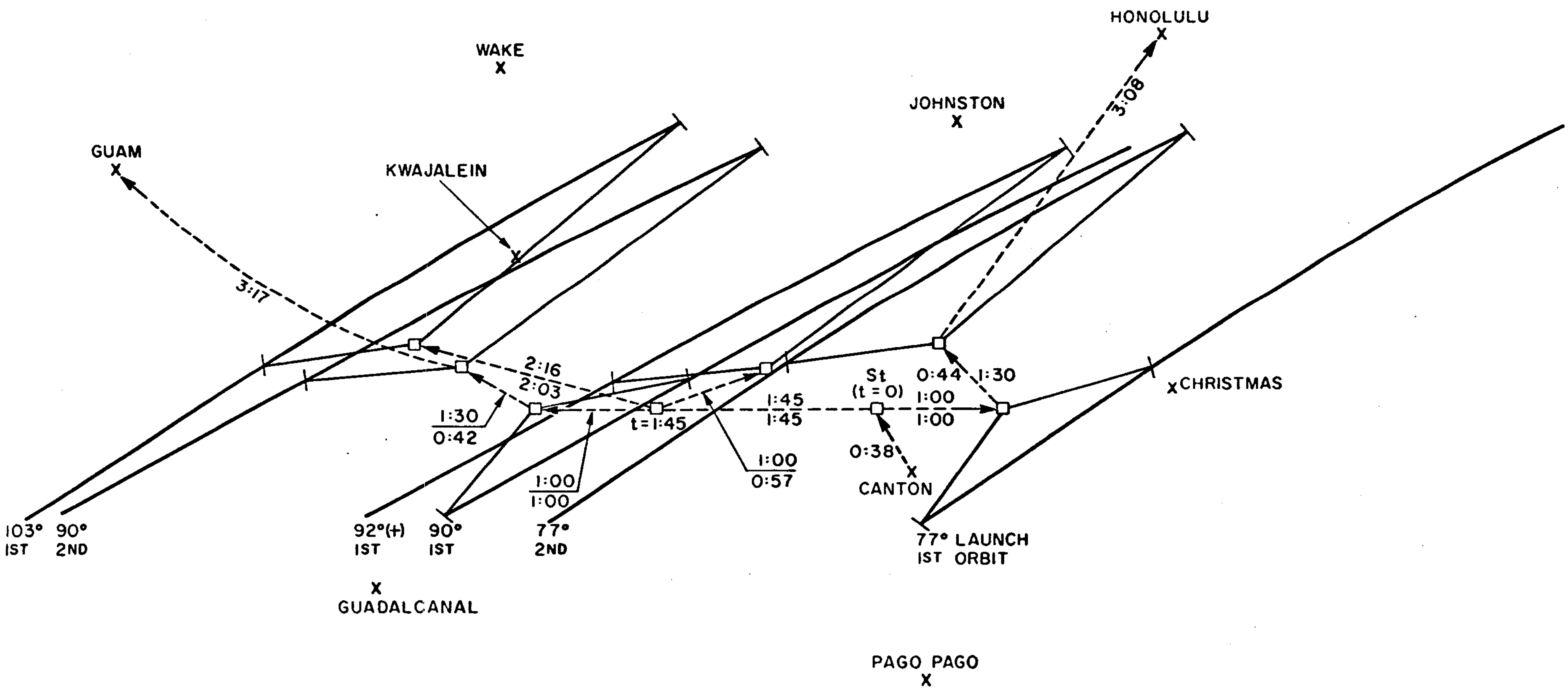


FIGURE 10

COVERAGE PROVIDED BY AIRCRAFT NO. 2
FOR INJECTION ON 1ST, 2ND, OR 3RD ORBITS
(NL + 6 ARRIVAL AT MOON, INJECTION OVER PACIFIC)

APPENDIX A

RECORDING SYSTEM

PRE-DETECTION VS. POST-DETECTION

This appendix reviews the merits of pre-detection and post-detection recorder-reproducers and concludes that the former is more suitable for the airborne application. It also contains the results of a brief survey of existing, magnetic tape, pre-detection recorders.

Since immediate analysis of the signals from the spacevehicle is not required, it is not necessary to provide demodulation, baseband terminal, or data processing equipment in the aircraft. This makes it possible to employ the pre-detection recording process in the aircraft, thus providing a fairly obvious advantage: the amount of equipment to be carried in the aircraft is much smaller than for post-detection recording techniques. A decrease in the quantity of equipment should increase the operational range and on-station time of the aircraft. These are important factors when considering the deployment of an aircraft for this particular mission.

Another major advantage of pre-detection recording is that it provides an opportunity to employ optimum demodulation* techniques on the recordings at a ground station. On the ground there are not the space, and hence equipment, limitations which might restrict one to simple demodulation techniques. Such techniques necessitate some demodulation loss relative to the optimum that might be obtained with more sophisticated, and usually more complicated, equipment. The possibility of adjusting to the demodulation technique that is most effective in combating the propagation conditions under which the signal was recorded is very appealing. Certainly some analysis of the recording on the ground would produce some characteristics of the signal that would assist in selecting the best means of extracting the signal from the modulated carrier. For instance, the Doppler shift of the signal might be ascertained and the center frequency of the receiver might be programmed to account for it. This would enable one to keep the noise bandwidth within the IF signal bandwidth.

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*"Demodulation" is used in a broad sense; "signal retrieval" might be a more descriptive term.

Primarily from the viewpoint noted above, advocates of pre-detection recording techniques point out that, with such techniques, the output signal-to-noise ratio can be improved over what would normally be achieved in a standard telemetry receiver. As much as 3 db of "system threshold improvement" is quoted when optimum demodulation is used. One manufacturer claims that even when a standard receiver is used as the demodulator for the pre-detection-reproduction process, a 6 db improvement in the FM threshold of subcarriers on FM/FM systems was provided in evaluation tests. This improvement was attributed to the fact that the signal was passed through the receiver IF limiter stages two times: once during the recording process and the second time during the reproduce process. The conclusion from the above seems to be that standard telemetry receivers are not designed to provide optimum detection of every signal. Hence, the pre-detection recording and reproduction technique along with optimum demodulation at a ground station might provide a 6 db improvement in present system operation.

Another advantage pointed out by the manufacturer is that pre-detection systems have an inherent immunity from tape dropout caused by irregularities in the magnetic properties of the tape. They report that data can be recovered even during a 90 per cent tape dropout. They also note that the dropout must be large enough to cause loss of 4 to 6 cycles of the carrier before degradation to the data occurs.

Operationally, pre-detection provides a versatility and flexibility that post-detection cannot; for example, most telemetry signals can be recorded on a pre-detection basis without special concern for the format of the data messages. Aircraft so instrumented could be used for a variety of missions and projects.

RECORDER SPEED AND BANDWIDTH

The considerations above lead to the conclusion that pre-detection recording has many desirable advantages, but the question still remains, "Will it meet the requirements for the airborne recording of the Apollo spacevehicle's communications." The answer to this comes from a survey of the capabilities of pre-detection recording equipment. Table A-1 describes five recorder-reproducers on which information was readily available. The characteristics noted are those which have a direct bearing on the general flexibility of this particular application. Other characteristics, such as power requirements, weight, operating temperature range, wow and flutter, dynamic skew, rewind time, input and output levels, etc. will have to be considered in the detailed engineering phase.

It is found that each of them can record up to 14 channels simultaneously (on one inch tape) and this is more than adequate for the eleven-track requirement. The minimum recording time for the recorder-reproducers is 12 minutes, which is ample for the maximum radio contact period of 9-1/2 minutes. Mylar tape of one mil thickness (9,000 feet on 14" reels) would have to be used on the Fairchild L-4000 to provide adequate recording time. However, all other equipments could use either 1-1/2 mil (7200 feet on 14" reels) or one mil tape.

The bandwidth capability of the recording channels in the several equipments is about 1.5 mc and this is sufficient for all of the VHF channels and the IU S-band channel. In the case of the CSM Unified S-band system, one step of demodulation is required to reduce the signal bandwidth below 1.5 mc. The IRIG Telemetry Standards Revised June, 1962, states that the bandwidth of the modulated carrier from a telemetry transmitter in the band 216 to 260 megacycles shall not exceed 500 kc. Channel allocations are based on this premise. Therefore, the 1.5 mc bandwidth reported for the recorder-reproducers listed in Table A-1 is more than adequate for handling the VHF and the IU S-band channels.

The case of the Unified S-band System is another story, principally because we must examine each of the possible modes of operation and determine the character of its frequency spectrum. In mode F (emergency voice) the carrier is directly frequency modulated by the voice with a modulation index of 1.0 radian. According to Carson's rule, the approximate RF, or IF, bandwidth is:

$$B_{IF} = 2\ b\ (M+1)$$

where b = width of baseband, 3 kc
and M = modulation index

With a voice baseband of three kc, the minimum bandwidth of the spectrum would be 12 kc. Even with a large allowance for the Doppler effect when communicating with fast moving objects this bandwidth can easily be accommodated on the tape recorder.

In the cases of modes A and B-1, the highest subcarrier (1250 kc) must be used to estimate the bandwidth. This subcarrier is to be frequency modulated by the 3 kc voice baseband with a modulation index of 2.50 radians (that is, a peak frequency deviation of 7.5 kc). Using Carson's rule again, the signal bandwidth would be about 21 kc and would extend from 1239.5 kc to 1260.5 kc. The latter value represents the highest frequency in the subcarrier's spectrum. In modes A and B-1, the main carrier is to be phase modulated by the subcarriers and the ranging signal at low modulation indices. All significant components of the RF spectrum will be contained within a band equal to two baseband widths on each side of the carrier. This amounts to about five mc and is well beyond the capabilities of the recording equipment. However, after one step of demodulation the multiplexed subcarrier baseband (highest frequency about 1.26 mc) fits within the frequence response specification of all except one recorder. Hence, S-band signals from the CSM will require a phase demodulator in the aircraft.

Since the modulated signal has a number of components with definite phase relationships between them, and particularly since the highest S-band signal components come close to the upper edge of the record-reproduce frequence response bandwidth (1.5 mc), the envelope delay distortion of the recorder-reproducer must be kept under control. At the time of the survey only one envelope delay curve was available (CM100). Although no difficulties are anticipated in obtaining an adequate envelope delay distortion characteristic, this should be examined in more detail.

Table A-1

CHARACTERISTICS OF PRE-DETECTION RECORDING EQUIPMENT

Known Record/ Reproduce System Suppliers	Model No.	Simultaneous Recording Channels 1/2" Tape	1" Tape	Recording Time - Min. (14" Reels) 7200' of Tape	9000' of Tape	Tape Speed ips	Direct Record/ Reproduce Freq. Response (±3db)	RMS Signal to RMS Noise Ratio	Envelope Delay Characteristics	Displacement Error µsec.	Solid State
Ampex Corporation Video/ Instrumentation Div.	FR-1400	7	14	12	15	120	400cps to 1.5Mc	20db	Not given	±250 at 60 ips	YES
Bell & Howell - Consolidated Electrodynamics Div.	VR-3600	7	14	12	15	120	400cps to 1.5Mc	20db	Not given	±250	YES
Fairchild - Winston Research Corp.	L-4000	7	14	8	12	180	800cps to 2.25Mc	25db	Not given	±0.2 at 60 ips	YES
Minnesota Mining & Manufac'ng	TICOR II	7	14	12	15	120	400cps to 1.5Mc	25db	Not given	±0.5 at 120 ips	YES
Mincom Div.	CM 100	7	14	12	15	120	400cps to 1.2Mc	28db	±1.0µsec. in band	Not given	NO

Other Possible Suppliers:

Honeywell Industrial Products Group
Potter Instrument Company, Inc.
Sangamo Electric Company
Midwestern Instrument Company
Precision Instrument Company